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EVALUATION OF BONDED BORON/EPOXY DOUBLERS FOR COMMERCIAL AIRCRAFT ALUMINUM STRUCTURES

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ABSTRACT

An 18 month laboratory test and stress analysis program was conducted to evaluate bonded boron/epoxy doublers for repairing cracks on aluminum aircraft structures. The objective was to obtain a core body of substantiating data which will support approval for use on commercial transports of a technology that is being widely used by the military. The data showed that the doublers had excellent performance.

DISCUSSION

About 2000 bonded boron/epoxy doublers have been successfully flying on U.S. and Australian aircraft since the mid-1970s, with another 2000 being installed by the U.S. Air Force in 1993-1994 on the C141 fleet (wing weep-hole riser cracks). The advantages include reduced installation cost and increased fatigue life, as well as other performance benefits.

There are also about 50 boron/epoxy doublers successfully flying for evaluation on U.S. and Australian commercial aircraft, including 25 on 2 Federal Express 747s since early 1993 (these are demonstration "decal" doublers on undamaged structure -- see Chart #2 for locations).

To help accelerate the transition of the bonded boron/epoxy doubler technology to commercial aircraft, Textron Specialty Materials sponsored a program to obtain a core body of test data which was projected to be required by the FAA and its international counterparts for approval for commercial aircraft applications. This program was conducted by the Boeing Company. The mechanical properties and performance tests were performed at Integrated Technologies (Intec).

This paper presents a synopsis of the results. There were four basic efforts in the program, as summarized in Chart #3 and described below.

1) Materials Specification. Materials properties data were obtained on three lots of 225°F cure boron/epoxy (designated #5521 by Textron) to support an existing Aerospace Materials Society specification (AMS # 3867/4A). Chart #4 summarizes the tests conducted.

2) Doubler Installation Process Specification. A doubler installation specification was written which included surface preparation (degrease, abrade, phosphoric acid anodize, and prime); adhesive; boron ply lay up and cure; and inspection (ultrasonic) including reference standards. Existing Boeing specifications for all procedures and materials (other than boron) were used (e.g., BMS 5-101 for 180°F performance structural adhesive; BMS 5-89 for primer; etc.). Chart #5 summarizes the process. It is available in written form and a training video has also been made and is available.

   The effects of various deviations from the doubler curing process (pressure, temperature, heat-up rate) and primer cure rate were evaluated on bond strength (lap shear). The results are summarized in Chart #6. The doubler cure process is quite robust in that relatively large variations from the baseline process do not significantly affect the lap shear bond strength. Note: based on these tests, 15" Hg (vacuum bag) cure was established as the baseline cure pressure.

3) Finite Element Analyses (FEA). 2-D and 3-D linear elastic FEA were conducted to support the performance test program (see Item #4 below). Key items investigated were the stresses in the bondline, the aluminum, and the boron/epoxy for three loads and two structural boundary conditions. The three loads were (1) thermal load due to the differential coefficients of thermal expansion (CTE) and the 225°F cure, (2) 15 ksi applied tensile load, and (3) combined thermal and tensile load. The two structural boundary conditions were for the doubler edge ending near-to (1.3") and far-from (4.3") an underlying stringer. Chart #7 presents a summary of the results.

   The key observation is that the shear and peel stresses in the adhesive due to the thermal load are of about the same value, but act in the opposite direction, to those stresses from the 15 ksi applied tensile load. A possible important implication of this is that a higher adhesive stress exists when the aircraft is on the ground vs in flight (for tensile-loaded structures), which could lead to increased inspection confidence of the bond. More sophisticated analyses (e.g., elastic-plastic using temperature-varying adhesive properties) are recommended to investigate this point further.

   Another key observation was that the peak axial stress concentrations in the aluminum and boron/epoxy were both lower for the combined load than for the 15 ksi applied tensile load. Thus, again, the residual thermal stresses have a beneficial effect.

4) Performance Tests (Laboratory). This was the largest effort of the program. It consisted of 110 static ultimate tension and 143 tension fatigue tests of boron/epoxy doublers bonded to 7075-T6 aluminum sheet (i.e., a relatively brittle aluminum) which had a 0.5" long sawcut (to simulate a crack) with a 0.25" diameter stop-drill. Chart #8 defines the test protocol. In general the specimens were fabricated per the installation specification of Item #2 above.

The tests were very successful and the results are summarized in Charts #9 through #11. The boron/epoxy doublers restored the static ultimate strength of the aluminum (80 ksi A/B statistical minimum value). Failure was almost always in the aluminum outside the doubler.

The fatigue tests were conducted at 3 ksi to 20 ksi (sine wave) at 5Hz, with 300,000 cycles being considered runout. (See Chart #8 for rationale for this condition which is considered a relatively severe "envelope" condition). Runout was successfully achieved with no crack re-initiation for the baseline boron/epoxy doubler geometry as long as the stop-drill was defect-free (e.g., no burrs). For reference, control specimens with no doubler (but with the stop-drilled 0.5" long sawcut) failed at 3100 cycles (average) -- thus more than a factor of 100X lower life. Post-fatigue static ultimate tension tests on the baseline configuration showed no degradation in static strength.

The effects of a number of variables and conditions on fatigue life were also evaluated. For many of these variables, the effect was negligible (i.e., no crack re-initiation after 300,000 cycles). These variables included: doubler geometry and ply lay up; 1.0 inch long crack; thinner aluminum; impact of 100 and 300 inch lbs. in line with the crack just beyond the stop drill; 1 month at 185°F - 85% humidity hot wet environment; 1 week immersion at 120°F in Skydrol; 1 Hz (sine and square wave) and Spectrum (with no compression) fatigue cycles; cure pressure (5 inch to 28 inch of Hg vacuum); and the presence of 0.5" diameter (deliberate) voids at the edge of the bondline and over the stop-drilled hole.

Variables which did result in crack re-initiation (but not necessarily crack propagation across the width of the specimen) included too few plies; no stop-drill; -65°F and cycle hot-cold (a 3 to 18 ksi stress cycle may eliminate crack initiation at these conditions); and 0 to 18 ksi load with no lateral restraint. Chart #11 summarizes the results. For those conditions where the crack re-initiated (from the stop-drilled hole), the crack grew at a linear reproducible rate, independent of crack length, and the boron/epoxy doubler carried the full load and had a post-fatigue (runout) static ultimate strength greater than 80 ksi for 96% of the specimens for which the crack did not emerge from under the doubler. In no case did the boron/epoxy doubler globally debond prior to the crack propagating the full width of the aluminum -- and most times, not even then, despite high twist loads (Ref Chart #8: the aluminum was 4 inches wide, the boron doubler was about 3 inches wide). In fact, 4 specimens with intact boron doublers on fully-cracked aluminum had a residual static ultimate strength of over 40 ksi (based on the original cross-sectional area of the aluminum). -- See Chart #10.

The overall conclusion of the test program is that viable materials and installation specifications have been written; the laboratory test data shows excellent performance; and the FEA help understand the interaction of the residual thermal stresses with the applied loads. This data should be very useful in supporting commercial aircraft applications of bonded boron/epoxy doublers. This laboratory data has also been successfully supported in flight evaluation of 25 "decal"* doublers on two Federal Express 747s (see chart #2). These doublers were installed in early 1993 and had over 700 flights as of late February 1994 and have performed excellently.

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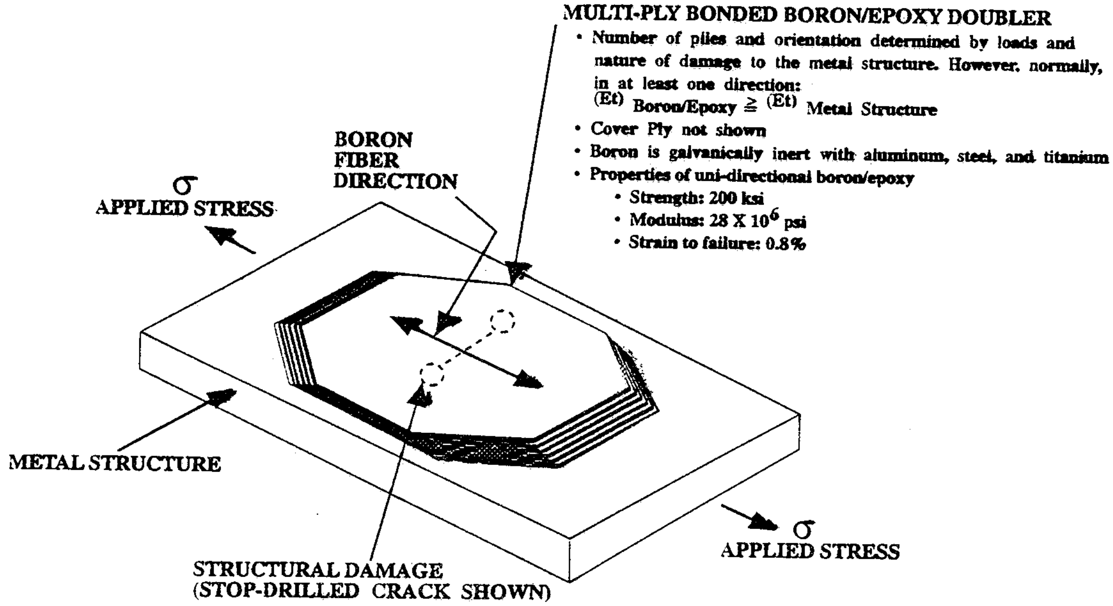
*The term "decal" means the doublers were applied to undamaged structure. The doublers, however, do carry about half the load in the primary load-carrying direction.

BONDED BORON/EPOXY DOUBLERS FOR REINFORCEMENT OF METALLIC AIRCRAFT STRUCTURES

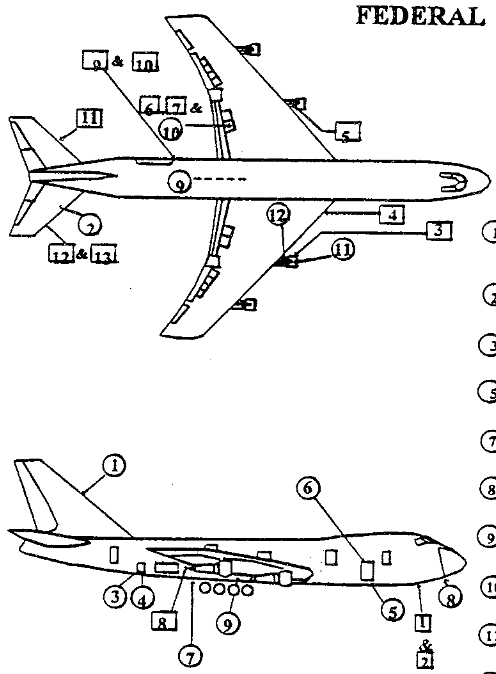


• THERE ARE ABOUT 4000 BORON/EPOXY DOUBLERS FLYING ON MILITARY AIRCRAFT AND 50 ON COMMERCIAL AIRCRAFT

CHART #1

LOCATION OF 25 BONDED BORON/EPOXY "DECAL" DOUBLERS ON 2 FEDERAL EXPRESS 747-200s

("Decal" Means The Doubler Is On Undamaged Structure, The Doubler Does Carry ~ 1/2 The Load In The Principal Stress Direction)



Aircraft: Fed Ex. #N639FE Line Number 354 Installation Date: Jan. 8-12, 1993		Aircraft: Fed Ex. #N631FE Line Number 406 Installation Date: March 1-5, 1993	
1	Vertical Stabilizer, Lower Forward Leading Edge, RH Side	1 & 2	Fuselage Belly Skin (6:00 Position) AFT of Nose Wheelwell
2	Horizontal Stabilizer, RH Side Of Leading Edge	3	Nose Cowl Inlet Lip Skin (8:00 Position)
3 & 4	Bulk Cargo Door Cut-out, Aft Side & Bottom	4	R/H Wing Leading Edge, Upper Airfoil Surface
5 & 6	Lower Cargo Door Cut-out, Bottom & Forward Side	5	No. 2 Engine Pylon, Inboard Skin Structure
7	Fuselage Belly Skin (6:00 Position)	6 & 7	L/H Inboard Wing Mid-Flap, Upper Skin
8	Nose Wheelwell Cutout, Forward Edge	8	R/H Aft Fuselage Skin (3:30 Position)
9	Main Landing Gear Wheelwell Canted Bulkhead Web	9 & 10	Main Cargo Door Cut-out, Forward Side
10	Wing-Mid Flap, Upper Skin	11	L/H Horizontal Stabilizer Leading Edge
11	Nacelle, Engine #3, Thrust Reverser Translating Sleeve	12 & 13	R/H Horizontal Stabilizer Leading Edge
12	Pylon, Engine #3, Inboard Side		

FLIGHT STATUS
• Planes Are In Daily Service ~ 700 Flights As Of February 1994
• Doublers Are Performing Excellently

CHART #2

LABORATORY TEST PROGRAM ON BONDED BORON/EPOXY DOUBLERS

OVERVIEW
- CONDUCTED BY THE BOEING COMPANY
- FUNDED BY TEXTRON SPECIALTY MATERIALS
- PERFORMANCE PERIOD: OCTOBER '92 THROUGH JULY '94

OBJECTIVE
- OBTAIN THE CORE BODY OF SUBSTANTIATING DATA REQUIRED FOR FAA APPROVAL

KEY EFFORTS

1) MATERIALS SPECIFICATION TESTS (AMS SPEC. #3867/4A)
   - PHYSICAL
   - CHEMICAL
   - MECHANICAL
   - BOND STRENGTH

VIDEO & WRITTEN SPEC. AVAILABLE

2) INSTALLATION PROCESS SPECIFICATION
   - SURFACE PREPARATION
   - ANODIZE (PAA)
   - PRIMER
   - ADHESIVE
   - CURING PROCEDURE
   - NDI PROCEDURES & REFERENCE STANDARDS
   - SENSITIVITY EFFECTS OF PROCESS DEVIATIONS

SEE CHARTS #3, 4, 5 & 7

3) PERFORMANCE TESTS
   - 110 STATIC TENSION
   - 143 TENSION-TENSION FATIGUE
     - GOAL: 300,000 CYCLES EACH

   } • BORON/EPOXY DOUBLERS BONDED TO 7075-T6 ALUMINUM WITH PRE-INDUCED CRACKS

SEE CHART#6

4) FEM STRUCTURAL DESIGN ANALYSIS/GUIDELINES FOR BONDED BORON DOUBLERS
   - LOAD TRANSFER
   - STRESS CONCENTRATIONS
   - EFFECTS OF BOUNDARY CONDITIONS (e.g. UNDERLYING RIBS, ETC.)
   - EFFECTS OF DIFFERENTIAL COEF. OF THERMAL EXPANSION (ALUMINUM VS. BORON/EPOXY)

CHART #3

PROPERTIES TESTS ON BORON/EPOXY TO VALIDATE AMS SPEC. #3867/4A

PHYSICAL [1]
- RESIN CONTENT
- VOLATILE CONTENT
- RESIN FLOW
- GEL TIME
- DENSITY
- POROSITY
- FLAMMABILITY

CHEMICAL [1]
- INFRARED SPECTROSCOPY
- LIQUID CHROMATOGRAPHY
- FLUID RESISTANCE
  - JP-4
  - DEICER
  - CLEANER
  - MIL-H-83282
  - SKYDROL

MECHANICAL [1]
- COMPRESSION
  - -67°F
  - ROOM TEMP.
  - 180°F WET
- SHORT BEAM SHEAR
  - -67°F
  - ROOM TEMP.
  - 180°F WET

TENSION
- -75°F
- ROOM TEMP.
- 180°F WET
- SKYDROL IMMERSION

} • 0° LAYUP & • 0°± 45° LAYUP

NOTE: 1) ALL TESTS WILL BE ON 3 BATCHES OF MATERIAL

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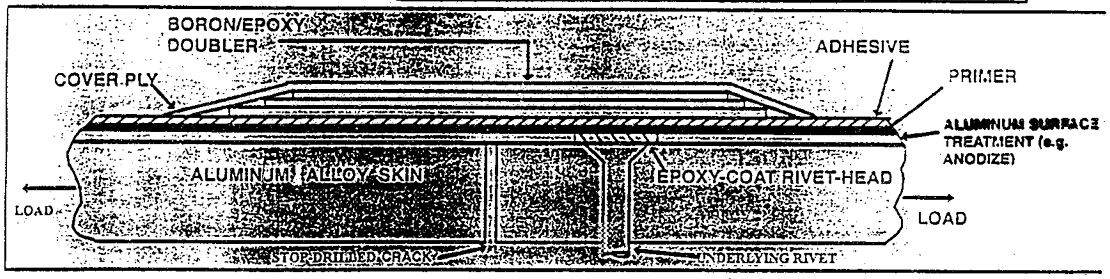
CHART #4

Installation Process For Bonding Boron Epoxy Doublers Onto Aluminum

- Uses *Existing* Technology, Materials, Specifications, and Equipment
- Uses Experienced *Composites Personnel*
- To Assure Proper Adhesion Requires *Process Control*



1) TRIAL RUN
- LOCATE DOUBLER
- SOLVENT CLEAN
- CURING UNIT RUN:
  - MEASURE SUBSTRATE TEMPERATURE PROFILE
  - CHECK ABILITY TO PULL VACUUM

2) SURFACE PREPARATION
- CLEAN
- REMOVE PAINT
- ABRADE(*WATER BREAK-FREE*)
- EPOXY-COAT UNDERLYING RIVET HEADS
- ANODIZE
  - *ACID ETCH 15 MINUTES*
  - *RINSE*

  } *PORTABLE EQUIPMENT: VACUUM BAG AND CONTAINERS, AND ANODE (Ref. Charts #9 & 10)*
  - *POLARIZED LIGHT INSPECTION TEST*
- PRIME (AIR DRY)
- COVER

3) DOUBLER INSTALLATION
- CUT AND LAY-UP BORON/PLIES
- PRE-CONSOLIDATE (IF THICK)

  } GENERALLY IS PREASSEMBLED
- APPLY ADHESIVE
- CO-CURE: BORON, ADHESIVE & PRIMER
  - RAMP TO 225°F @ 5°F/MIN
  - 90 MINUTES AT 225°F (107°C)
  - RAMP DOWN (~20 MINUTES)

  } USE PROGRAMMABLE PORTABLE VACUUM BAG-HEATER BLANKET UNIT (Ref. Charts #9 & 10)

4) INSPECT FOR BOND VOIDS AND DELAMINATIONS (ULTRASONIC & VISUAL)

5) SEAL AND PAINT TO OWNER'S SPECIFICATION

Written Specifications Exist For The Entire Process Shown, And All Materials

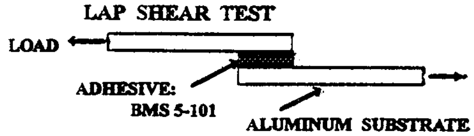
TEXTRON Specialty Materials

(Original figure unavailable at time of publication)

CHART #5

SENSITIVITY OF BOND STRENGTH TO VARIATIONS IN INSTALLATION PROCESS

LAP SHEAR TEST



BASELINE CURE CONDITION
- TEMPERATURE: 90 MINUTES @ 225°F
- HEAT-UP RATE: 5°F PER MINUTE
- CURE PRESSURE: 15" Hg (i.e. ~ HALF ATMOS. VACUUM)
- PRIMER CURE: AIR DRY

1) EFFECTS OF CURE PRESSURE

PRESSURE	*BOND STRENGTH**	
5" Hg	5190 PSI	
10" Hg	5230 PSI	
15" Hg	5730 PSI	} (2 DATA SETS)
15" Hg	5420 PSI	
28" Hg	4100 PSI	

2) EFFECT OF CURE TEMP. & TIME (AT 28" Hg)

CONDITION	*BOND STRENGTH**
90 MIN. @ 225°F	4100 PSI
90 MIN. @ 250°F	4230 PSI
180 MIN. @ 225°F	4390 PSI

**ALL VALUES SHOWN ARE THE AVERAGE OF 5 TESTS*

3) EFFECTS OF CURE HEAT-UP RATE

HEAT-UP RATE	*BOND STRENGTH**
5°F PER MINUTE	4230 PSI
1°F PER MINUTE	5140 PSI
10°F PER MINUTE	3960 PSI

4) EFFECTS OF PRIMER CURE RATE

PRIMER CURE COND.	*BOND STRENGTH**
HEAT LAMP CURE	4230 PSI
<30 MIN. AIR DRY	3960 PSI
AIR DRY (15" Hg CURE)	5730 PSI
BOIL PRIMER WITH HOT AIRGUN	4990 PSI

5) EFFECTS OF BORON PLY INSERTED IN MIDDLE OF ADHESIVE (15" Hg CURE)

CONDITION	*BOND STRENGTH**
NO BORON PLY	5730 PSI
WITH BORON PLY	5160 PSI

CONCLUSION: VERY ROBUST INSTALLATION PROCESS

CHART #6

ORIGINAL PAGE IS OF POOR QUALITY

FINITE ELEMENT STRESS ANALYSES

OBJECTIVE

- FIRST ORDER ESTIMATE OF CRITICAL STRESSES:
  - IN BONDLINE
  - IN ALUMINUM

  DUE TO

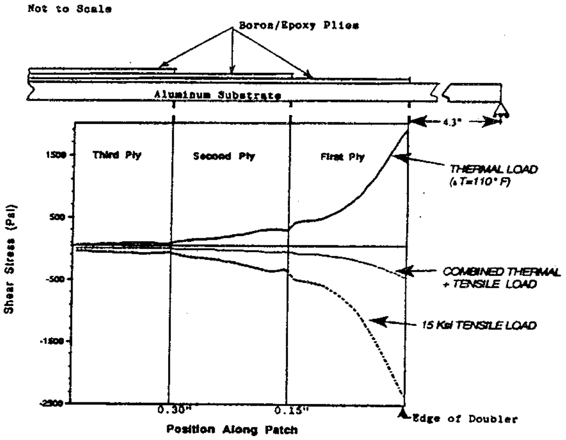
  - THERMAL LOAD (I.E., RESIDUAL CURE STRESSES DUE TO DIFFERENTIAL COEFFICIENTS OF THERMAL EXPANSION)
  - APPLIED 15 KSI TENSILE LOAD
  - COMBINED THERMAL + TENSILE LOADS

ANALYSES CONDUCTED

- MODELS USED:
  - 2-D: ANSYS + COSMOS M
  - 3-D: NIKE
- LINEAR ELASTIC
- USED ROOM TEMPERATURE PROPERTIES

KEY CONCLUSIONS

- RESIDUAL THERMAL STRESSES ARE SIGNIFICANT
- HOWEVER, IN THE ADHESIVE, SHEAR AND PEEL STRESSES ACT IN OPPOSITE DIRECTIONS FOR THERMAL VS TENSILE LOADS, AND ARE OF SIMILAR MAGNITUDE. THUS:
  - ADHESIVE LOADS ARE LOWER FOR COMBINED LOAD (E.G., IN FLIGHT).
  - AN AS-APPLIED DOUBLER ON UNLOADED STRUCTURE HAS HIGH ADHESIVE STRESSES -- IMPLIES IN-SITU "PROOF TEST" OF SORTS . . . NEEDS MORE SOPHISTICATED ANALYSIS.
- MAXIMUM TENSILE STRESSES IN ALUMINUM AND BORON ARE LOWER FOR COMBINED LOAD THAN FOR 15 KSI TENSILE LOAD ONLY.

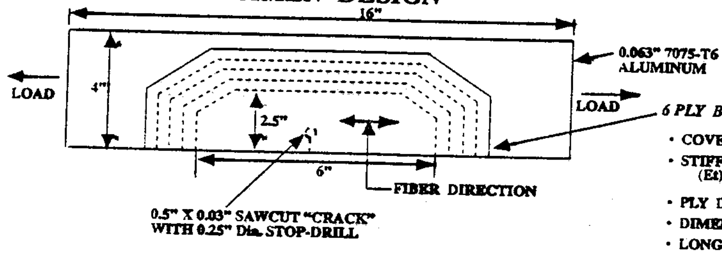


Shear Stress Distribution in Adhesive Layer

CHART #7

TEST PROTOCOL FOR PERFORMANCE TESTS

A. BASELINE SPECIMEN DESIGN



6 PLY BORON/EPOXY DOUBLER

- COVER PLY ON TOP
- STIFFNESS RATIO $(Et)_{B/E} \cong 1.4\ (Et)_{AL}$
- PLY DROP-OFF RATIO: 30 X PLY THICKNESS (≅ 0.15")
- DIMENSIONS OF SHORTEST PLY SHOWN
- LONGEST PLY ON BOTTOM
- 0° FIBER ORIENTATION (TO THE LOAD)
- FABRICATED PER THE INSTALLATION PROCESS SPECIFICATION (15" Hg CURE PRESSURE)

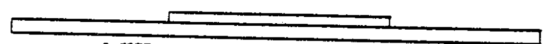
B. TEST CONDITIONS

1. STATIC ULTIMATE STRENGTH
   - GOAL: > 80 ksi: RESTORE A/B STATISTICAL MINIMUM FOR 7075-T6 ALUMINUM
2. FATIGUE LIFE①
   - 3 KSI TO 20 KSI @ 5 Hz
   - 300,000 CYCLES CONSIDERED RUNOUT
   - UNRESTRAINED SPECIMEN

   } • RELATIVELY CONSERVATIVE "ENVELOPE" CONDITION:
   - HIGH CYCLE FATIGUE LIFE @ HIGH STRESS
   - RELATIVELY BRITTLE ALUMINUM

① RATIONALE FOR FATIGUE TEST CONDITION

UNRESTRAINED CONDITION



3 KSI MINIMUM LOAD TO ELIMINATE THERMAL BENDING

AIRCRAFT	AIRCRAFT DESIGN OBJECTIVE	COUPON TEST FATIGUE OBJECTIVE	DESIGN STRESS	ESTIMATED EQUIVALENT DESIGN STRESS
737	75,000 CYCLES	300,000 CYCLES	0 TO 15 ksi	3 TO 17 ksi
747	20,000 CYCLES	80,000 CYCLES	0 TO 18 ksi	3 TO 20 ksi

CHART #8

KEY CONCLUSIONS FROM PERFORMANCE TESTS

OVERALL:

- EXCELLENT PERFORMANCE

STATIC ULTIMATE STRENGTH (TENSILE):

- THE BORON/EPOXY DOUBLER RESTORES THE PRE-CRACKED ALUMINUM TO ITS STATISTICAL A/B MINIMUM STRENGTH (80 KSI FOR 7075-T6 AL), INCLUDING ON POST-FATIGUED SPECIMENS (300 K CYCLES) WHERE THE CRACK HAS GROWN SIGNIFICANTLY (BUT IS STILL UNDER THE DOUBLER).

FATIGUE PERFORMANCE:

- BASELINE CONFIGURATION: NO CRACK RE-INITIATION AT 300,000 CYCLES (RUNOUT). (CONTROL SPECIMEN WITH NO DOUBLER FAILED AT 3100 CYCLES).
- BASELINE PERFORMANCE NOT AFFECTED BY:
  - VARIOUS DOUBLER GEOMETRIES
  - 0° VS 0° ± 45° BORON PLIES
  - LONGEST PLY ON BOTTOM VS. TOP
  - CURE PRESSURE (5" TO 28" Hg VACUUM)
  - ENVIRONMENTS: HOT-WET; SOLVENT
  - CRACK LENGTH OF 1.0"
  - THINNER ALUMINUM (0.032")
  - IMPACT @ 100 & 300 INCH-LBS.
  - 0.5" DIAMETER VOIDS OVER STOP-DRILL AND EDGE OF DOUBLER
  - 1 Hz AND SPECTRUM FATIGUE CYCLES
- CRACK RE-INITIATION[1] DOES OCCUR:
  - IF THERE WAS A DEFECT (E.G., BURR) IN THE STOP-DRILL
  - IF THE CRACK IS NOT STOP-DRILLED
  - IF THERE ARE TOO FEW PLIES (ESPECIALLY AS ALUMINUM GETS THICKER)
  - AT -65°F
  - AT LOAD OF 0 TO 18 KSI WITH NO LATERAL RESTRAINT
- IF/WHEN CRACK RE-INITIATION OCCURS:
  - THE BORON DOUBLER REMAINED INTACT (NO GLOBAL DISBONDS) AND CARRIED THE LOAD
  - CRACK GROWTH WAS AT A LINEAR REPRODUCIBLE RATE INDEPENDENT OF CRACK LENGTH

[1] THIS MEANS THE CRACK EMANATED FROM THE STOP-DRILL. IT DOES NOT NECESSARILY MEAN THE SPECIMEN FAILED.

CHART #9

SUMMARY OF STATIC ULTIMATE TENSION TEST RESULTS

BASELINE

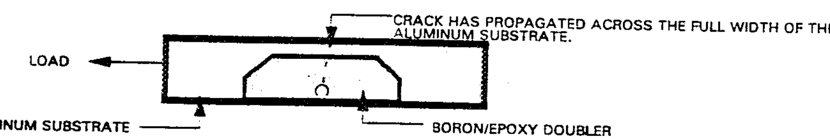
- 11 TESTS
- BORON/EPOXY DOUBLER RESTORES 80 KSI MINIMUM STRENGTH TO THE PRE-CRACKED ALUMINUM
  - ALMOST ALL SPECIMENS BROKE IN THE ALUMINUM OUTSIDE OF THE BORON/EPOXY DOUBLER
  - INCLUDES TESTS ON VARIOUS DOUBLER GEOMETRIES (NO EFFECT)

POST-IMPACT

- 2 TESTS
- GOOD STRENGTH RETENTION AT HIGH IMPACT (43 KSI @ 1200 INCH-LBS)

POST-FATIGUE (300,000 CYCLES)

- BORON DOUBLER RESTORES STATIC ULTIMATE STRENGTH -- EVEN IF THE CRACK PROPAGATES THE FULL WIDTH OF THE ALUMINUM BENEATH THE DOUBLER.
  - 97 TESTS (MANY VARIABLES -- SEE "SUMMARY OF FATIGUE TESTS" CHART)
    - 87 TESTS: $\geq$ 80 KSI
  - 25 HAD CRACK RE-INITIATION
    - 4 TESTS: 69 TO 76 KSI
    - 4 TESTS: 42 TO 44 KSI EQUIVALENT STRESS IN 4" X .063" ALUMINUM: THE CRACK HAD PROPAGATED ACROSS THE FULL WIDTH OF THE ALUMINUM. THE BORON DOUBLER WAS INTACT AND CARRIED THE INDICATED LOAD.



    - 2 TESTS: 76 KSI: SAME AS ABOVE, BUT DIFFERENT BORON DOUBLER CONFIGURATION (I.E., FULL WIDTH OF THE 4" ALUMINUM)

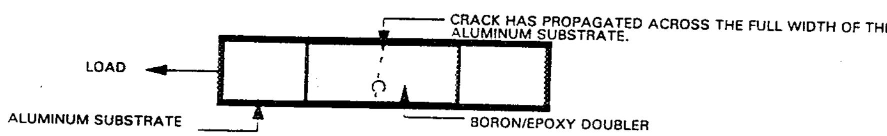


CHART #10

SUMMARY OF FATIGUE TEST RESULTS

PARAMETER/VARIABLE	NO. OF TESTS	RESULTS NO. TO 300K CYCLES, NO CRACK RE-INIT.[1]	NO. TO 300K CYCLES, WITH CRACK RE-INIT. AT NO. CYCLES SHOWN[2]	NO. TO < 300K CYCLES, WITH FAILURE @ NO. OF CYCLES SHOWN	REMARKS/CONCLUSIONS
1. BASELINE CONFIGURATION [3]	13	10	1 @ 113K	1 @232K } GRIP 1 @ 284K } FAILURES	• 300K RUNOUT ACHIEVED WITH MINIMAL CRACK RE-INIT.
2. CONTROL; NO DOUBLER	3	--	--	3 @ 3.1K AVG.	• LIFE DROPS BY FACTOR OF > 100
3. DOUBLER GEOMETRY EFFECTS • 0°VS 0° ±45° PLY LAYUP • LONGEST PLY ON BOTTOM VS TOP • SMALLER LATERAL SIZE (1.5" X 4") • WIDER DOUBLER (4" X 4") • 15:1 PLY DROP-OFF	30	14[4] 1	6 TOTAL, 1 EACH @ 87K*, 90K*, 168K, 244K*, 270K, & 283K	9 TOTAL, 1 EACH @ 141K, 145K, 134K, 141K, 74K, 202K, 181K, 212K & 225K	• DEFECTS FOUND IN STOP-DRILL IN ALL 9 SPECIMENS TO ≤ 300K CYCLES, PLUS THOSE WITH * • NO EFFECT OF VARIOUS GEOMETRIES
4. DOUBLER CURE PRESSURE (5" & 28" Hg)	6	6	--	--	• NO EFFECT
5. FEWER BORON PLIES (4 VS 6 IN BASELINE)	3	1	--	1 @ 254K; 1 @ 265K	• CLEAR DROP IN PERFORMANCE
6. ENVIRONMENTAL EXPOSURE • -65°F	6	2	4 TOTAL, 1 EACH @ 44K, 47K, 84K, & 188K	--	• CLEAR DROP IN PERFORMANCE @ -65°F
• -65°F WITH LATERAL RESTRAINT SET AT R.T. 3 KSI POSITION	2	--	1 @ 69; 1 @ 102	--	• NO CHANGE VS. NO RESTRAINT
• 165°F AFTER 1 MO. @ 180°F + 85% HUMIDITY.	3	2	1 @ 287K	--	• NO EFFECT
• CYCLIC: -65°F TO 165°F	3	1	1 @ 152K; 1 @ 217K	--	• SOME EFFECT
• 1 WEEK IN SKYDROL @ 120°F	3	3	--	--	• NO EFFECT
7. IMPACT[5] • 100 INCH-LB @ RT • 100 INCH-LB @ -65°F; RT FATIGUE • 100 INCH-LB @ 160°F; RT FATIGUE • 300 INCH-LB: REPEAT OF 100 INCH-LB MATRIX	3 3 3 9	3 3 3 8	-- -- -- --	-- -- -- 1@ 192K. FAILURE WAS OUTSIDE OF THE DOUBLER	• NO EFFECT

CHART #11. Pg. 1 of 3

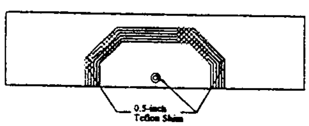
PARAMETER/VARIABLE	NO. OF TESTS	RESULTS NO. TO 300K CYCLES, NO CRACK RE-INIT.[1]	NO. TO 300K CYCLES, WITH CRACK RE-INIT. AT NO. CYCLES SHOWN[2]	NO. TO < 300K CYCLES, WITH FAILURE @ NO. OF CYCLES SHOWN	REMARKS/CONCLUSIONS
8. NO STOP DRILL	3	--	3[6]	--	• CRACK CLEARLY PROPAGATES, BUT BORON DOUBLER KEEPS SPECIMEN INTACT (2 SPECIMENS CRACKED ACROSS ENTIRE WIDTH)
9. 1.0" LONG CRACK	3	3	--	--	• NO EFFECT
10. OTHER FATIGUE SPECTRA • 1 Hz SINE WAVE • 1 Hz SQUARE WAVE • SPECTRUM LOAD (NO COMPRESSION)	1 1 3	1 1 3	-- -- --	-- -- --	• NO EFFECT
11. ALTERNATE LOADS • 0 TO 18 KSI • 0 TO 18 KSI WITH LATERAL RESTRAINT SET AT 3 KSI POSITION	3 2	1 2	-- --	1 @ 175K; 1 @ 236K --	• CLEAR DROP IN PERFORMANCE IF NO LATERAL RESTRAINT.
12. VOIDS (0.5"D) IN BOND OVER STOP-DRILL HOLE AND AT DOUBLER EDGE (SEE B-2 CONFIG) • TEST @ RT • CYCLIC: -65°F to 165°F	3 3	2 1	1 @ 149K 1 @ 147K; 1@ 211K	-- --	• MODEST EFFECT ON CRACK RE-INIT. (MOSTLY @ -65°F -- SEE ITEM #6 ABOVE). NO TENDENCY TO CAUSE DOUBLER DEBOND.
13. RIVET (PLUG) AT OUTSIDE EDGE OF DOUBLER (AT HIGH STRESS POINT IN AL.) (SEE B-3 CONFIG)	1	1	--	--	• NO EFFECT
14. THINNER ALUMINUM (0.032") • CONTROL: NO BORON DOUBLER • 0.5" CRACK BORON DOUBLER • 1.0" CRACK HAD 4 PLIES[7]	3 3 3	-- 3 3	-- -- --	AVG OF 3: 4.3K -- --	• NO EFFECT OF THINNER AL • REPEAT OF ≥ 100X INCREASE IN PERFORMANCE.

PARAMETER/VARIABLE	NO. OF TESTS	RESULTS: NO. TO 300K CYCLES, NO CRACK RE-INIT.[1]	NO. TO 300K CYCLES, WITH CRACK RE-INIT. AT NO. CYCLES SHOWN[2]	NO. TO < 300K CYCLES, WITH FAILURE @ NO. OF CYCLES SHOWN	REMARKS/CONCLUSIONS
15. THICKER ALUMINUM (0.10")					• REPEAT: LOW LIFE WITH NO DOUBLER • 8 PLIES OF BORON (ON 1 SIDE) INSUFFICIENT. (THIS SUPPORTS CONCLUSION OF ITEM #5 ABOVE). NOTE THAT 8 PLIES GIVES BORON: AL. STIFFNESS RATIO OF ONLY 1.1 VS 1.4 FOR 6 PLIES ON .063" AL. (SEE NOTE #8). INCREASE TO 10 PLIES HELPS GREATLY (1.4 STIFF. RATIO). 11 OR 12 PROBABLY BEST DESIGN, OR 4 PLIES ON EACH SIDE.
• CONTROL: NO BORON DOUBLER	3	--	--	AVG. OF 3: 5.1K	
• 0.5" CRACK (8 PLY BORON DOUBLER[8])	3	--	--	AVG. OF 3: 129K	
• 1.0" CRACK (8 PLY BORON DOUBLER[8])	3	--	--	AVG. OF 3: 48K	
• 0.5" CRACK, CYCLIC: -65°F TO 165°F (8 PLY BORON DOUBLER[8])	3	--	--	AVG OF 3: 111K	
• 0.5" CRACK: (10 PLY DOUBLER[9])	3	1	1 @ 134K	1 @ 144K	
• 0.5" CRACK 0 TO 18 KSI (10 PLY DOUBLER[9])	3	--	--	AVG. OF 3: 126K	
• 0.5" CRACK: 8 PLY DOUBLER, WITH 4 PLIES ON EITHER SIDE	3	2	--	1 @ 210: FAILED OUTSIDE OF DOUBLER	
TOTAL	143				

NOTES:

1 RE-INIT. IS ABBREVIATION FOR RE-INITIATION.
2 ALL CYCLES ROUNDED TO NEAREST 1000.
3 SEE CHART #3 FOR DEFINITION.
4 3 TESTS WERE AT 3 TO 15 KSI.
5 THE IMPACT SITE WAS ON THE BORON IN LINE WITH THE STOP DRILL ABOUT 0.25" BEYOND THE STOP DRILL.
6 NO. OF CYCLES TO CRACK RE-INITIATION NOT MEASURED.
7 THIS RESULTS IN A STIFFNESS RATIO OF 1.8 ($(Et)_{B.E.} \div (Et)_{AL}$) VS 1.4 FOR 6 PLIES OF BORON EPOXY ON 0.063" AL.
8 THIS RESULTS IN A STIFFNESS RATIO OF 1.1 ($(Et)_{B.E.} \div (Et)_{AL}$) VS 1.4 FOR 6 PLIES OF BORON EPOXY ON 0.063" AL.
9 THIS INCREASES THE STIFFNESS RATIO TO 1.4

Configuration B-2



Configuration B-3

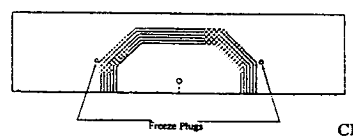


CHART #11, Pg. 3 of 3